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Enhanced soil moisture improves vegetation growth in an arid grassland of Inner Mongolia Autonomous Region, China

ZHANG Hui[1,2], Giri R KATTEL[1,3], WANG Guojie[1], CHUAI Xiaowei[4], ZHANG Yuyang[1], MIAO Lijuan[1,2*]

[1] School of Geographical Sciences, Nanjing University of Information Science & Technology, Nanjing 210044, China;
[2] State Key Laboratory of Remote Sensing Science, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100094, China;
[3] Department of Infrastructure Engineering, the University of Melbourne, Melbourne 3010, Australia;
[4] School of Geography & Ocean Science, Nanjing University, Nanjing 210093, China

Abstract: Climate change impacts on grasslands that cover a quarter of the global land area, have become unprecedented during the 21st century. One of the important ecological realms, arid grasslands of northern China, which occupy more than 70% of the region's land area. However, the impact of climate change on vegetation growth in these arid grasslands is not consistent and lacks corresponding quantitative research. In this study, NDVI (normalized difference vegetation index) and climate factors including temperature, precipitation, solar radiation, soil moisture, and meteorological drought were analyzed to explore the determinants of changes in grassland greenness in Inner Mongolia Autonomous Region (northern China) during 1982–2016. The results showed that grasslands in Inner Mongolia witnessed an obvious trend of seasonal greening during the study period. Two prominent climatic factors, precipitation and soil moisture accounted for approximately 33% and 27% of grassland NDVI trends in the region based on multiple linear regression and boosted regression tree methods. This finding highlights the impact of water constraints to vegetation growth in Inner Mongolia's grasslands. The dominant role of precipitation in regulating grassland NDVI trends in Inner Mongolia significantly weakened from 1982 to 1996, and the role of soil moisture strengthened after 1996. Our findings emphasize the enhanced importance of soil moisture in driving vegetation growth in arid grasslands of Inner Mongolia, which should be thoroughly investigated in the future.

Keywords: grassland growth; normalized difference vegetation index; climate change; soil moisture; Inner Mongolia

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1 Introduction

The impacts of climate change on grasslands, which cover a quarter of the global land surface area, have become unprecedented during the 21st century. Arid grasslands, the major vegetation realms, contribute to more than 40% of the global net primary productivity (Grace et al., 2006). Therefore, arid and semi-arid grasslands not only sustain the world's population through food production, but also regulate carbon cycling (Poulter et al., 2014; Huang et al., 2017a). However,

*Corresponding author: MIAO Lijuan (E-mail: miaolijuan1111@gmail.com)
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recent studies have shown that vegetation in arid grasslands is becoming increasingly vulnerable to external environmental changes, including climate change (Deng et al., 2020; Nandintsetseg et al., 2021). One of the largest drylands in Asia, the grasslands in Inner Mongolia, China currently face unprecedented challenges of its sustainability due to global climate warming. For instance, the temperature increased as high as 0.37°C/10 a, which was 2.5 times higher than the global mean value (i.e., 0.14°C/10 a) during 1961–2012 (Hu et al., 2015). The frequency and intensity of climatic extremes (e.g., extreme winter snowstorms and summer droughts) have also markedly increased in Inner Mongolia since the 2000s (John et al., 2013). These changes have posed serious threats to the stability of the grassland ecosystem and the sustainable livelihoods of local farmers and pastoralists in the region than any time before (Li et al., 2023). Understanding the relationship between vegetation growth and climate change is especially important in ecological research. Therefore, detecting degradation or greening trends of the vegetation in grasslands and their climate drivers are crucial in developing effective grassland management practices and maintaining the socio-ecological integrity of local grassland biomes.

Lately, satellite observations have been widely used for the simulation of vegetation growth at large spatial scales of China, including Inner Mongolia (Zhu et al., 2016; Bai et al., 2019). Spectral vegetation indices, such as normalized difference vegetation index (NDVI), are often used to approximate grassland vegetation greenness (Zhang et al., 2016; Kang et al., 2021) under various climatic constraints especially water stress (Fan et al., 2016; Miao et al., 2020; Wang et al., 2022a). Although the effects of precipitation on hydrology and vegetation growth were described comprehensively by previous studies (Tong et al., 2017; Li et al., 2018; Wang et al., 2022b), there were limitations to those studies as only a portion of precipitation is directly absorbed by vegetation due to interception, evaporation, and surface runoff (Lee et al., 2018). Soil moisture plays a significant role in the dynamics of plant photosynthesis, respiration process, and evapotranspiration because water stored in the roots of vegetation is absorbed directly to support plant's growth and greenness (Li et al., 2021). The interaction between soil moisture and precipitation determines the utilization efficiency of water by vegetation (Liu et al., 2020). Previous studies have shown that the combination of precipitation and soil moisture can better explain the changes in vegetation greenness in arid areas (Warter et al., 2021). Moreover, an increased frequency and severity of drought, resulting in severe root water scarcity, can also markedly affect grassland vegetation greenness in arid areas (He et al., 2019). Therefore, considering the role of soil moisture and meteorological drought in the context of precipitation is crucial for understanding the interaction between water stress and grassland vegetation greenness.

The mechanisms behind the effect of soil moisture on grassland vegetation greenness in Inner Mongolia are yet to be comprehensively understood. To fill this gap, we additionally considered soil moisture regime and meteorological drought as two major climatic factors that control the amount of water in Inner Mongolia to determine grassland vegetation greenness. The primary purpose of this study is therefore to explore the determining role of water-related climatic factors on the vegetation greenness of Inner Mongolian grasslands and quantify their contributions over the past 35 a. Secondly, we further explore how the strength of climate factors affecting the vegetation greenness of Inner Mongolian grasslands over a long-term period, especially whether there will be a shift in the dominant factor.

2 Materials and methods

2.1 Study area

The Inner Mongolia Autonomous Region (37°24′–53°23′N, 97°12′–126°04′E) of China is situated in the middle of the Eurasian steppe belt, covering a total area of 1.18×10^6 km^2. This region is characterized by typical temperate continental monsoon climate, featuring extremely cold-dry winter and hot-moist summer (Bao et al., 2014). Its climate condition gradually transits from semi-humid in the east to semi-arid and arid in the central and western regions, due to its vast

east-west span. The annual mean temperature in Inner Mongolia ranges from –5.50°C to 3.10°C, while the mean annual precipitation varies from 234 to 418 mm (Guo et al., 2021). Grasslands are the dominant vegetation types in Inner Mongolia with an area of approximately 0.68×10^6 km^2 (Wang et al., 2017). Accompanied by the varying gradients in climatic characteristics in Inner Mongolia, the major grassland types vary from meadow steppe in the northeast to typical steppe in the middle and desert steppe in the west.

2.2 Datasets

2.2.1 NDVI

To characterize vegetation greenness dynamics, we utilized bimonthly NDVI data from global inventory modeling and mapping studies (GIMMS $NDVI_{3g}$) (Tucker et al., 2005; Pinzon and Tucker, 2014). This dataset has a spatial resolution of 8 km and covers the period from 1982 to 2016 (https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/). GIMMS $NDVI_{3g}$ dataset was generated routinely from calibrated advanced very high resolution radiometer (AVHRR). Data issues caused by sensor degradation, inter-sensory differences, cloud cover, and solar zenith angle due to satellite drift and volcanic aerosols, have been well addressed (Tucker et al., 2005). This dataset provides the longest time series data available for monitoring vegetation growth and phenology at regional and global scales (Piao et al., 2011; Fensholt and Proud, 2012; Luo et al., 2021). During the calculation, we removed pixels with an annual mean NDVI of less than 0.1, as these pixels may have sparse vegetation or lack noticeable seasonal vegetation growth features (Huang et al., 2017b). Grassland vegetation greenness mentioned in this study was defined by the average NDVI during the growing season from April to October (i.e., $NDVI_{GS}$).

2.2.2 Climate dataset

Climatic variables were extracted from Chinese Meteorological Forcing Dataset (CMFD, http://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49/). The dataset includes gridded observations of monthly average temperature (°C), monthly average downward shortwave radiation ($\times10^6$ J/m^2), and monthly total precipitation (mm) at a spatial resolution of 0.1°×0.1° from 1982 to 2016. CMFD was developed by the Data Assimilation and Modeling Center for Tibetan Multi-spheres at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (He et al., 2020). The dataset was fused with multiple products, including remote sensing images, reanalysis datasets, and weather station records. It has been widely utilized in previous studies related to climate change (Yang et al., 2017; Wang et al., 2019).

2.2.3 Soil moisture

Due to the scarcity of *in-situ* measurements, soil moisture data relies heavily on satellite retrievals and model simulations to a great extent. Here, we used a daily 0.25° spatial resolution soil moisture (m^3/m^3) dataset (1982–2016) derived by the European Space Agency (ESA) Climate Change Initiative program on the global monitoring of Essential Climate Variables (CCI-SM v.4.7, https://www. esa-soilmoisture-cci.org). ESA CCI-SM represents surface soil moisture at a depth of 2–5 cm, and it is generated by two active and seven passive microwave products (Wagner et al., 2012). This product could reflect the seasonal and inter-annual dynamics of the original satellite-derived retrievals (Liu et al., 2012). An et al. (2016) has demonstrated its good performance in analyzing China's grassland dynamics. Yao et al. (2021) used 0–10 cm soil moisture site measurement data released by China Meteorological Network to verify the accuracy of ESA CCI-SM grid data. The results also showed that ESA CCI-SM data had a good consistency with the site measurement data in summer and autumn in Inner Mongolia. These two seasons comprised the main part of the growing season as defined in this study. Here, we averaged the original daily product to the monthly scale.

2.2.4 Standardized precipitation evapotranspiration index (SPEI)

We used an SPEI dataset with a monthly grid size of 0.5° (Beguería et al., 2010; Vicente-Serrano et al., 2010) to analyze drought conditions in Inner Mongolia from 1982 to 2016 (SPEIbase v. 2.6,

https://spei.csic.es/database.html). SPEI is a measure of drought, which takes into account the historical probability distribution of precipitation minus potential evapotranspiration. High and low SPEI values signify relatively moist and dry conditions, respectively (Beguería et al., 2010). This calculation method considers the effects of water evaporation and transpirations, and can describe drought characteristics at multiple temporal scales. Here, we utilized the 3-month SPEI (SPEI-3) to identify short-term drought events in Inner Mongolia because the SPEI-3 could conceivably produce its highest correlations with NDVI to a great extent (Vicente-Serrano et al., 2013).

2.2.5 Land cover product

Land use information was extracted from moderate resolution imaging spectroradiometer (MODIS) land cover product (MCD12C1 v. 6.0, https://lpdaac.usgs.gov/products/mcd12c1v006/). It spans from 2001 to 2015 and features a spatial resolution of 0.05°. In this study, we merged grasslands, closed shrublands, and open shrublands into a single category that captures potential grasslands in the study area. To ensure spatial compatibility between MODIS land cover product (i.e., grassland layer) and other datasets (e.g., NDVI, temperature, precipitation, solar radiation, soil moisture, and SPEI), we resampled these datasets to a uniform spatial resolution of 0.25°. All calculations were performed in pixels labeled with constant grasslands from 2001 to 2015 to minimize the influence of land cover change.

2.3 Methods

Multiple linear regression (MLR) and boosted regression tree (BRT) were applied to quantify the relative contributions of different factors to changes in grassland greenness over Inner Mongolia. By comparing the results from these two methods, we sought to validate our analysis and ensure the robustness of our findings. For each pixel, we initially calculated the relative contributions of each factor to changes in grassland $NDVI_{GS}$ and identified the dominant factor during the period 1982–2016. Then, the study period was separated into two segments of 15 a (i.e., 1982–1996 and 2002–2016) to examine whether the primary factor driving changes in grassland $NDVI_{GS}$ trends has shifted over the past 35 a.

2.3.1 MLR

MLR is a statistically regression-based method. We quantified the relative contributions of each determinant (e.g., temperature, precipitation, solar radiation, soil moisture, and SPEI-3) as follows:

$$\mathrm{NDVI_{GS}} = b_0 + b_1\mathrm{Tmp} + b_2\mathrm{Pre} + b_3\mathrm{Rad} + b_4\mathrm{SM} + b_5\mathrm{SPEI} + \varepsilon, \quad (1)$$

where b_i is the regression coefficients for each variable, including Tmp for the average temperature (°C), Pre for the total precipitation (mm), Rad for the average solar radiation (J/m^2), SM for the average soil moisture (m^3/m^3), and SPEI for the standardized precipitation evapotranspiration index; and ε is the other determinant that is not considered but might contribute to changes in grassland $NDVI_{GS}$.

We performed MLR using R package "relaimpo", which is based on variance decomposition for MLR models and provides six different methods for analyzing the relative contribution of each regressor determinant in linear regression (Grömping, 2007). Among these methods, we chose the most commonly used ones, LMG (Lindeman, Merenda, and Gold) methods, because of its strength in differentiating the relative contribution of correlated regression variables. LMG method estimated the relative contribution of each variable by decomposing the sum of squares into non-negative contributions shared by each variable, and LMG values were obtained by averaging the sequential sum of squares (R^2) for all possible orders. Finally, all values of relative importance were normalized (divided by R^2) to sum to 1. This method has been widely used in the attributions of vegetation growth (Huang et al., 2018; Wu et al., 2019). Additionally, we used the standardized regression coefficient of multiple linear regression to characterize positive or negative influence of each factor on grassland $NDVI_{GS}$.

2.3.2 BRT

BRT is a machine learning-based method that combines the advantages of regression trees and

boosting (Elith et al., 2008). The former generates trees by recursive binary splits, with explanatory variables and split points selected to minimize prediction errors. Booting combines many trees in a forward-stagewise process to improve predictive performance further. Compared with other statistical approaches, BRT has fewer requirements for data structure and is less influenced by correlated information or irrelevant variables (Crase et al., 2012; Dormann et al., 2013). These characteristics make BRT well-suited to handle complex nonlinear relationships, such as the marginal effect and relative contribution of each independent variable on the response variable (Elith et al., 2008). We calculated the marginal effect of an individual predictor variable based on the assumption that other independent variables remain constant, and this effect will be regarded as the relative contribution to the response variable. Here, we used BRT to quantify the relative contributions of each determinant in grassland $NDVI_{GS}$ in Inner Mongolia during the period 1982–2016. $NDVI_{GS}$ was the dependent variable, while temperature, precipitation, solar radiation, soil moisture, and SPEI-3 were the independent variables. We conducted BRT using the R package "gbm". A detailed explanation of BRT can be found in Elith et al. (2008).

3 Results

3.1 Changes in Inner Mongolia's grassland $NDVI_{GS}$ and its determinants from 1982 to 2016

The grassland vegetation growth in Inner Mongolia, as measured by $NDVI_{GS}$, witnessed an overall greening trend at a rate of 0.006/10 a from 1982 to 2016 (P<0.01; Fig. 1a). During the same period, the growing season has experienced a significant increase in mean temperature by 1.61°C (P<0.05; Fig. 1b). Total precipitation and mean soil moisture have also displayed slightly increasing trends (P>0.05; Fig. 1c and d). In contrast, mean radiation and SPEI-3 both decreased

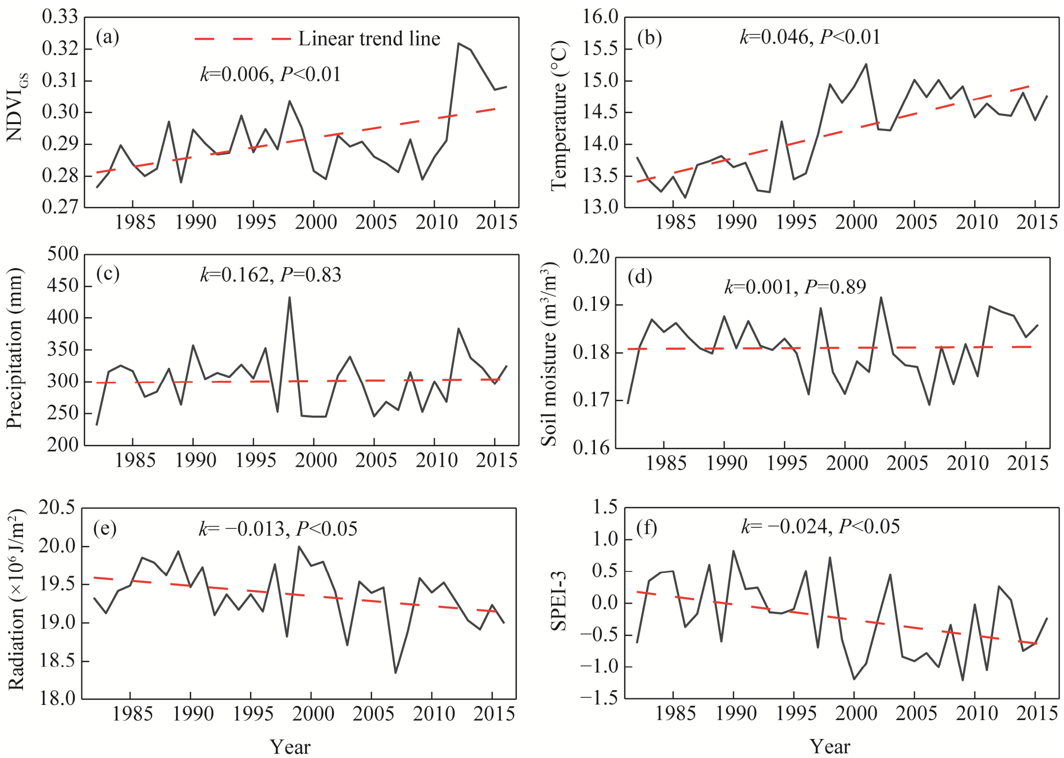

Fig. 1 Changes in grassland $NDVI_{GS}$ (grassland vegetation greenness measured by normalized difference vegetation index (NDVI)) (a), temperature (b), precipitation (c), soil moisture (d), radiation (e), and SPEI-3 (3-month standardized precipitation evapotranspiration index) (f) in Inner Mongolia during the growing season from 1982 to 2016. k and P denote the slope and P-value of each variable, respectively.

significantly (P<0.05; Fig. 1e and f). It should be noted that the temporal trends in precipitation and soil moisture were relatively consistent with $NDVI_{GS}$ trend, indicating that changes in grassland $NDVI_{GS}$ in Inner Mongolia may be closely related to water availability.

Over the past three decades, approximately 74% of the grassland areas in Inner Mongolia has exhibited increasing trends in $NDVI_{GS}$ (significant in 61% of the areas, P<0.05; Fig. 2a). However, a decrease in $NDVI_{GS}$ was observed in 26% of the grassland areas (significant in 8% of the areas, P<0.05), primarily in central and eastern regions of Inner Mongolia. Meanwhile, the increasing trend in temperature was more apparent, accounting for 98% of the grassland areas in Inner Mongolia (significant in 95% of the areas, P<0.05; Fig. 2b). It should be noted that about 60% of the grassland areas in Inner Mongolia showed a drying trend, with a significant decrease in the SPEI-3 (P<0.05; Fig. 2c). The observed patterns of droughts were consistent with the climatic warming, as high temperatures were expected to increase atmospheric evaporative demand, leading to severe droughts. Additionally, the total precipitation displayed spatial

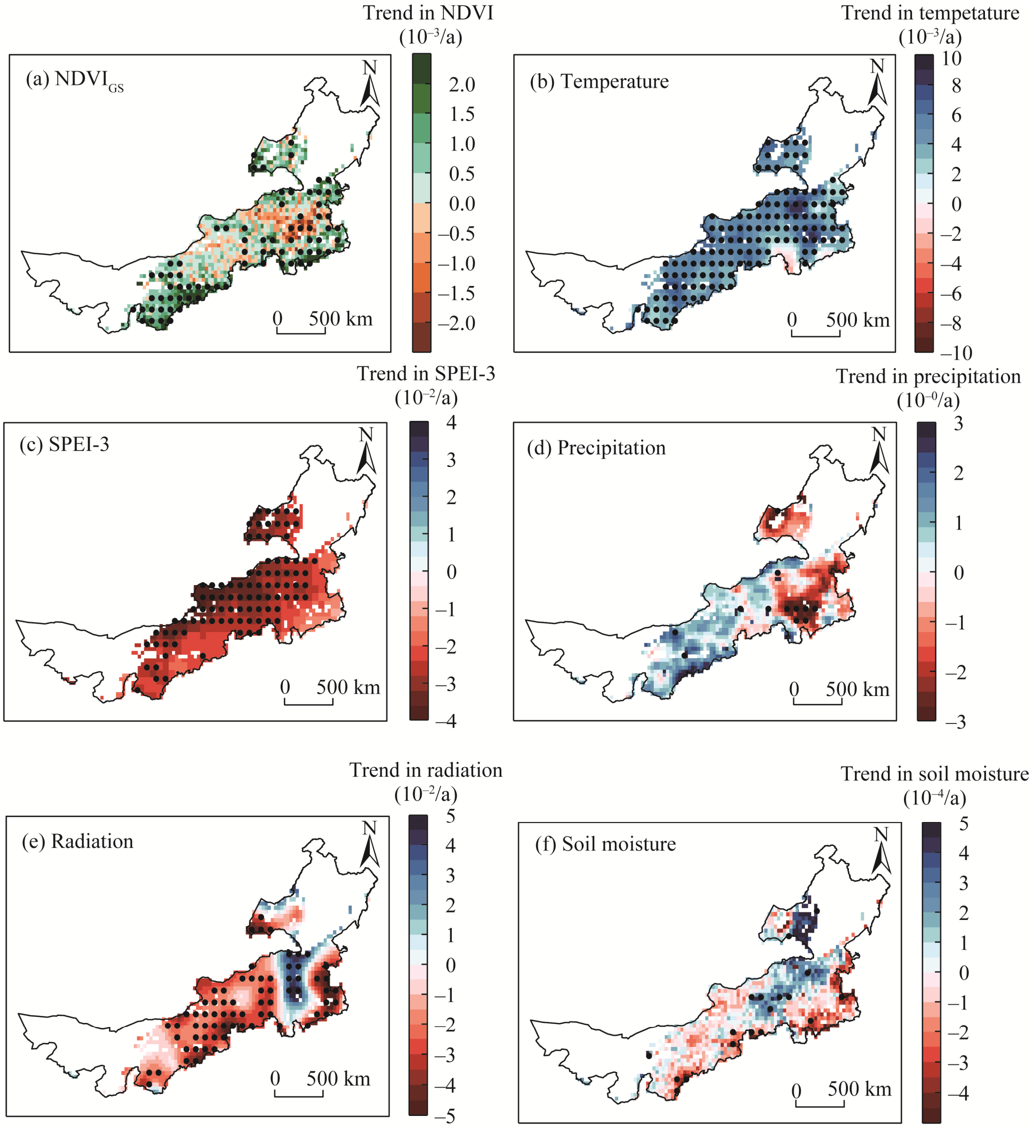

Fig. 2 Spatial pattern of grassland $NDVI_{GS}$ (grassland vegetation greenness measured by normalized difference vegetation index (NDVI) (a), temperature (b), SPEI-3 (3-month standardized precipitation evapotranspiration index (c), precipitation (d), radiation (e), and soil moisture (f) in Inner Mongolia during the growing season from 1982 to 2016. Regions with significant trends (P<0.05) were marked in black dots.

heterogeneity, with a decrease in the east (significant in 44% of the areas) and an increase in the west (significant in 56% of the areas; Fig. 2d). In particular, spatial distribution of precipitation and $NDVI_{GS}$ trends exhibited similarities, especially in areas with significantly low precipitation. In contrast, radiation showed an overall opposite trend with $NDVI_{GS}$ (Fig. 2e), suggesting that changes in vegetation growth observed in the grasslands of Inner Mongolia were likely influenced by changes in water availability. Although the replenishment of soil moisture in dryland deeply relies on precipitation, spatial distribution of soil moisture trends differed from that of precipitation (Fig. 2f). Increased soil moisture (significant in 47% of the areas) was mainly observed in northeastern and central regions of Inner Mongolia, while a decreasing trend of soil moisture (significant in 53% of the areas) was evident in southeastern and western regions of Inner Mongolia.

3.2 Determinants of changes in grassland $NDVI_{GS}$ and their contributions

BRT and MLR methods delivered similar spatial distributions of primary factors of grassland $NDVI_{GS}$ trends in Inner Mongolia (Fig. 3). Both methods identified precipitation and soil moisture as two primary factors of changes in grassland $NDVI_{GS}$, dominating about 33% and 27% of the areas of changes in grassland $NDVI_{GS}$, respectively. SPEI-3 was found to be another factor closely linked to water availability and was estimated to have dominated around 14% of changes in grassland $NDVI_{GS}$ (12% and 16% estimated by BRT and MLR, respectively). These findings suggest that changes in water availability play a critical role in determining the growth of grassland vegetation in Inner Mongolia. Compared with the determinants related to water availability (i.e., precipitation, soil moisture, and SPEI-3), temperature and solar radiation played a smaller role in driving changes in grassland $NDVI_{GS}$, accounting for only 15% and 10% of the changes, respectively. Furthermore, these regions were fragmentally distributed in southeastern and southwestern Inner Mongolia. These findings highlight the importance of precipitation and soil moisture in regulating changes in grassland $NDVI_{GS}$ over Inner Mongolia.

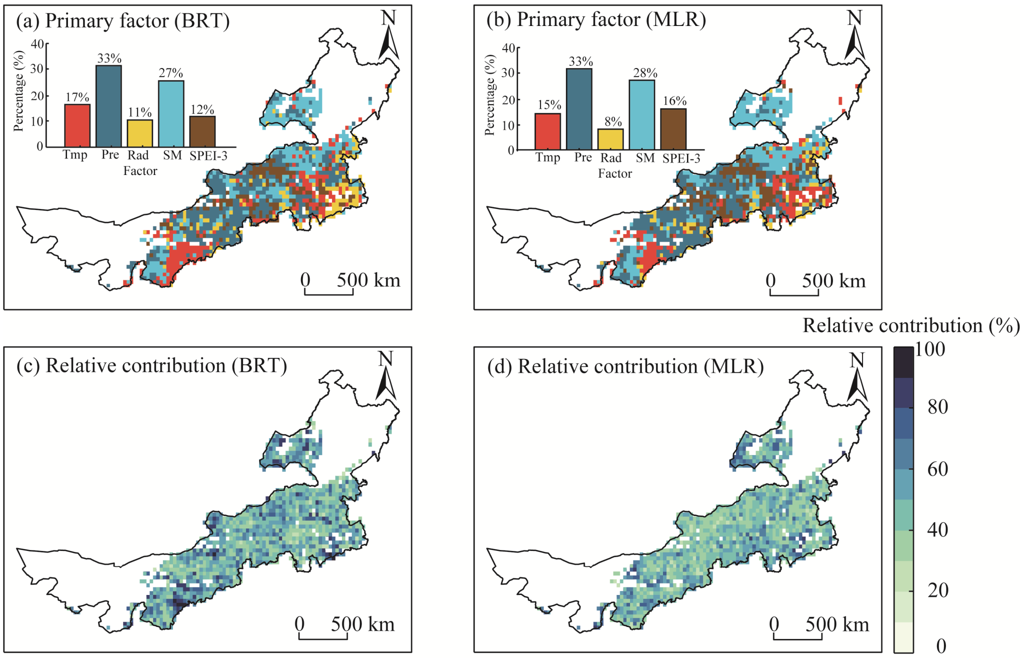

Fig. 3 Spatial distributions of primary factor influencing grassland $NDVI_{GS}$ (grassland vegetation greenness measured by normalized difference vegetation index (NDVI)) in Inner Mongolia during the period 1982–2016, and their relative contributions estimated by BRT (boosted regression tree) and MLR (multiple linear regression). (a), primary factor estimated by BRT; (b), primary factor estimated by MLR; (c), relative contributions estimated by BRT; (d), relative contributions estimated by MLR. Primary factor indicated in each grid cell was defined as the driving factor that contributes the most to changes in $NDVI_{GS}$. Driving factors include Tmp (temperature), Pre (precipitation), Rad (radiation), SM (soil moisture), and SPEI-3 (3-month standardized precipitation evapotranspiration index).

We also further investigated whether primary factors of grassland $NDVI_{GS}$ changes in Inner Mongolia shifted over the past 35-a time scale. We divided the research period into two 15-a intervals (1982–1996 and 2002–2016) and analyzed the spatial distribution of primary factors during each interval using both BRT and MLR methods. Our results showed that precipitation and SPEI-3 were the dominant factors affecting grassland $NDVI_{GS}$ changes during the first 15-a interval, with precipitation playing a more important role according to BRT analysis and SPEI-3 according to MLR analysis (Fig. 4a and b). Meanwhile, temperature, solar radiation, and soil moisture had relatively weak influences. This indicated that precipitation and drought were primary factors of $NDVI_{GS}$ changes during the period 1982–1996. During the second 15-a interval (2002–2016), soil moisture was found to be the dominant factor affecting grassland $NDVI_{GS}$ changes, accounting for approximately 38% of the grassland areas according to both BRT and MLR analyses (Fig. 4c and d). In contrast, the areas dominated by precipitation and SPEI-3 during the first 15-a interval significantly decreased, and their roles were replaced by soil moisture. These findings highlight the enhanced importance of soil moisture in improving grassland $NDVI_{GS}$ changes across Inner Mongolia, especially over the past two decades.

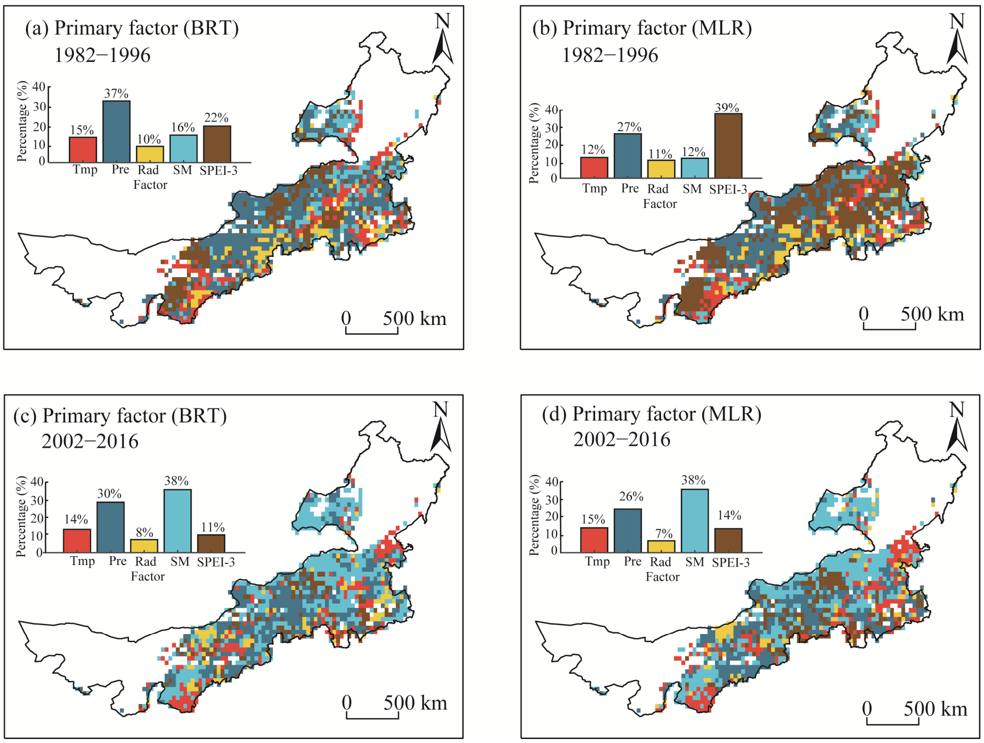

Fig. 4 Spatial patterns of primary factor influencing grassland $NDVI_{GS}$ (grassland vegetation greenness measured by normalized difference vegetation index (NDVI)) estimated by BRT (boosted regression tree) and MLR (multiple linear regression) methods in Inner Mongolia for two sub-periods (i.e., 1982–1996 and 2002–2016). (a and b), primary factors estimated by BRT and MLR from1982 to 1996; (c and d), primary factors estimated by BRT and MLR from 2002 to 2016. The five factors include Tmp (temperature), Pre (precipitation), Rad (radiation), SM (soil moisture), and SPEI-3 (3-month standardized precipitation evapotranspiration index).

3.3 Positive or negative influence of driving factors in grassland $NDVI_{GS}$

Using standardized regression coefficient obtained from MLR method, we conducted a further analysis to investigate the positive or negative influence of each driving factor on grassland $NDVI_{GS}$ in Inner Mongolia (Fig. 5). In general, we observed a positive correlation between temperature and grassland $NDVI_{GS}$, accounting for around 71% of the grassland areas (significant in 23% of the areas, P<0.05; Fig. 5a). Conversely, a negative influence of temperature on

grassland $NDVI_{GS}$ was observed in only 29% of the grassland areas (significant in 3% of the areas, $P<0.05$). Climatic variables related to water availability, such as precipitation, soil moisture, and SPEI-3, were found to have a positive impact on grassland $NDVI_{GS}$ in Inner Mongolia, accounting for 86%, 79%, and 65% of the grassland areas, respectively (Fig. 5b–d). These factors significantly and positively influenced 20%, 24%, and 11% of the grassland areas, respectively ($P<0.05$).

The areas with significantly positive precipitation influence were mainly concentrated in the west, while the grassland $NDVI_{GS}$ change induced by soil moisture was observed in the north and south. Precipitation and soil moisture primarily showed an increasing trend along with the grassland greening (Fig. 2). However, water scarcity condition as shown by grassland browning was consistent with SPEI-3 trend in the central area (Fig. 2). In the case of solar radiation, no significant changes in grassland $NDVI_{GS}$ were observed (Fig. 5e).

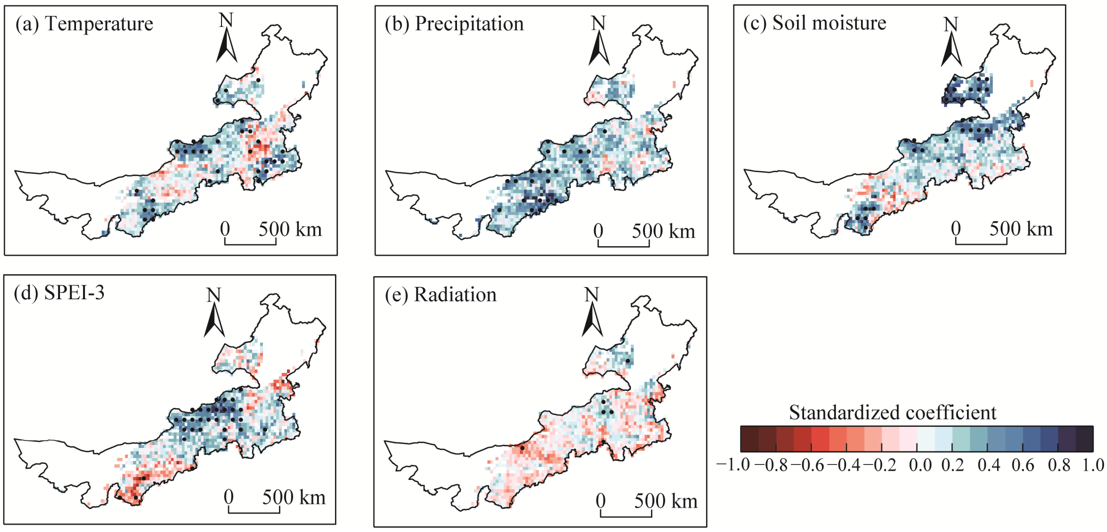

Fig. 5 Spatial patterns of influential factors of temperature (a), precipitation (b), soil moisture (c), SPEI-3 (3-month standardized precipitation evapotranspiration index; d), and radiation (e) on grassland $NDVI_{GS}$ (grassland vegetation greenness measured by normalized difference vegetation index (NDVI)) based on standardized coefficient calculated from multiple linear regression. Regions with statistically significant ($P<0.05$) influence are labelled with black dots.

Given the changes in primary factors of Inner Mongolia's grassland $NDVI_{GS}$ over the past three decades (Fig. 4), we further tested whether the positive or negative influence of these factors could also vary. During the period 1982–1996, approximately 64% of the areas showed a positive influence of temperature on grassland $NDVI_{GS}$ (significant in 16% of the areas, $P<0.05$), which was primarily observed in northeastern and central Inner Mongolia (Fig. 6a). However, over the past 15 a, areas with positive correlations between temperature and grassland $NDVI_{GS}$ declined to 46% (significant in only 5% of the areas, $P<0.05$; Fig. 6b). Specially, influence of temperature on the changes in grassland $NDVI_{GS}$ in northeastern Inner Mongolia switched from a significant positive influence (during the first 15-a interval from 1982 to 1996) to a non-significant and negative influence (during the second 15-a interval from 2002 to 2016). These results indicate that the influence of warming over the past few decades appears to have declined.

In both periods, approximately 50% of the grassland areas was under positive and negative influence of solar radiation (Fig. 6c and d). Precipitation, which is primary source of water in the area, positively influenced grassland $NDVI_{GS}$ in Inner Mongolia in both periods, covering approximately 70% and 72% of the grassland areas, respectively, and 11% and 13% of these areas were significant at $P<0.05$ level (Fig. 6e and f). For most grassland areas, short-term drought (as

indicated by SPEI-3) positively influenced grassland $NDVI_{GS}$ during the first 15-a interval, covering 76% of the grassland areas, where 20% were significant ($P<0.05$; Fig. 6g). However, positive influence of short-term drought was noticeably weakened during the second 15-a interval, with only 3% of the grassland areas being significant ($P<0.05$; Fig. 6h). In contrast to SPEI-3, soil moisture had limited positive influence on grassland $NDVI_{GS}$ compared with precipitation and SPEI-3 from 1982 to 1996, covering about 58% of the grassland areas, where only 6% was significant ($P<0.05$; Fig. 6i). Nevertheless, approximately 77% of the grassland areas showed a positive influence of soil moisture on grassland $NDVI_{GS}$ from 2002 to 2016, where 27% were significant ($P<0.05$; Fig. 6j). Standardized soil moisture coefficient value increased significantly during the second 15-a interval compared with the first 15-a interval, indicating that soil moisture control in Inner Mongolia's grassland $NDVI_{GS}$ was strengthening over the last three decades.

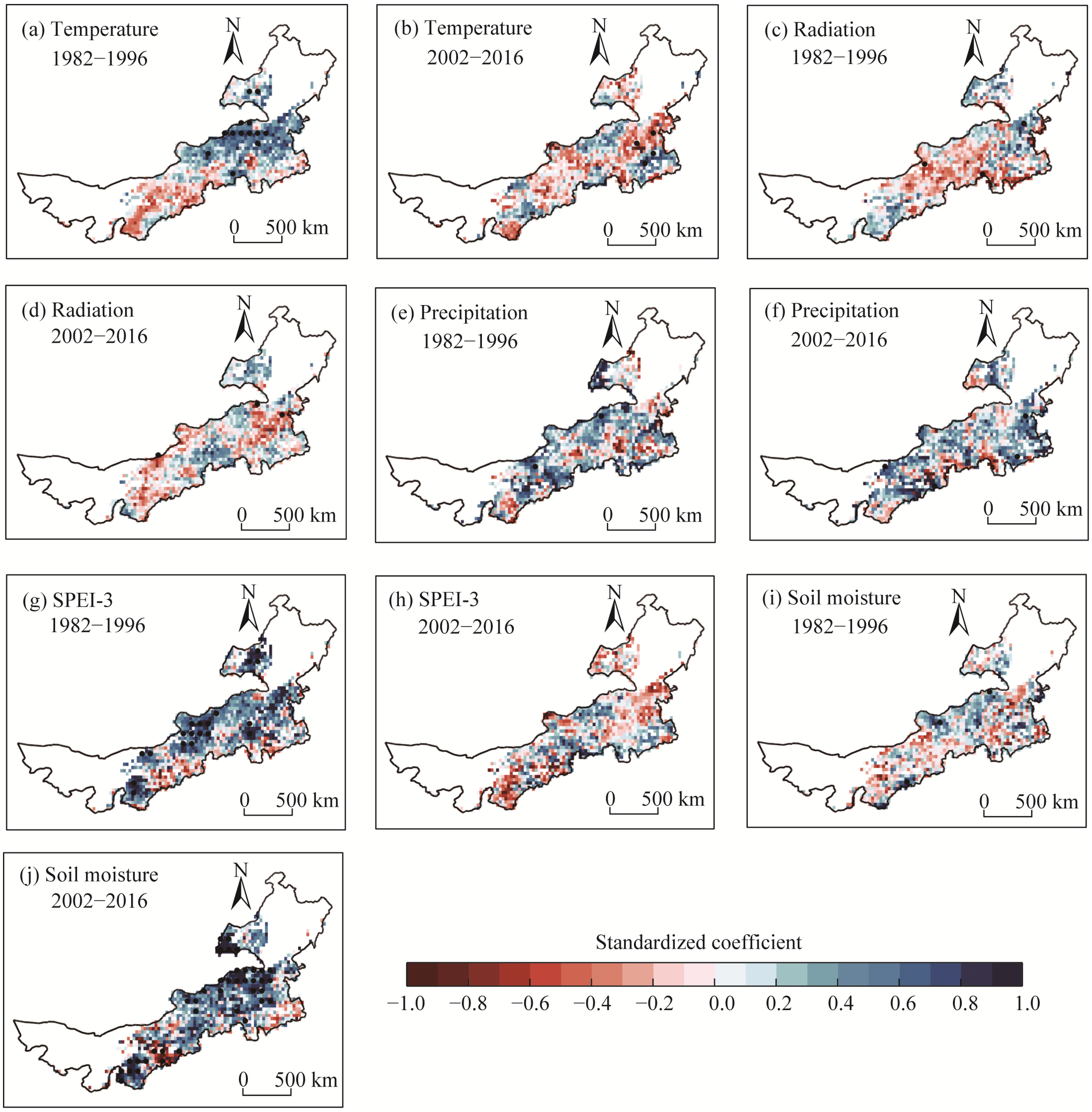

Fig. 6 Spatial patterns of influence of temperature (a and b), radiation (c and d), precipitation (e and f), SPEI-3 (3-month standardized precipitation evapotranspiration index, g and h), and soil moisture (i and j) on grassland $NDVI_{GS}$ (grassland vegetation greenness measured by normalized difference vegetation index (NDVI)) by standardized coefficient calculated from multiple linear regression during two sub-periods (i.e., 1982–1996 and 2002–2016). Regions with statistically significant ($P<0.05$) influence are labelled with black dots.

4 Discussion

4.1 Moisture-dominant grassland greening in Inner Mongolia

Detection and attribution of observed changes in grassland vegetation greenness are crucial for understanding grassland ecosystems and for sustainable management and development of these ecosystems in arid and semi-arid regions worldwide. Our study suggested that grasslands in Inner Mongolia experienced an overall vegetation greening trend from 1982 to 2016, which is consistent with many previous studies (Guo et al., 2014; Miao et al., 2020; Zhang et al., 2021). Vegetation greenness is typically associated with meteorological elements, such as temperature-controlled vegetation growth in tundra at high latitudes of northern hemisphere, and solar radiation-controlled vegetation growth in low-latitudes tropical rainforests (Wu et al., 2015). Moisture is usually the dominant factor controlling vegetation growth in arid and semi-arid areas in mid-latitude regions including China's Inner Mongolia (Wang et al., 2015). Given its proximity to mid-latitude dryland area, Inner Mongolia is exposed to limited moisture regime. Most previous studies used precipitation as the key climatic factor to characterize moisture conditions in the region (Zhang et al., 2019; Shi et al., 2020) without realizing the mechanisms behind the dynamics of moisture in arid area. Precipitation must be converted to soil moisture before this can be further utilized by plants (Li et al., 2021). Soil moisture was found to have reflected the amount of available water in arid grasslands more accurately (Zhou et al., 2021). In Inner Mongolia, deficit of soil moisture would largely limit the growth of pasture (Nakano et al., 2008). Our results also confirmed that observed grassland greening trend in Inner Mongolia was influenced by precipitation and soil moisture, highlighting the response of vegetation growth to changing moisture conditions in arid regions.

4.2 Enhanced control of soil moisture on grassland vegetation growth

We noted that contribution and area influenced by soil moisture on observed grassland greening in Inner Mongolia were not entirely suggestive of being a primary factor (Fig. 3). However, the role of soil moisture was second only to that of precipitation suggesting the importance of soil moisture in vegetation growth in arid grasslands. Based on soil moisture output from hydrological models, Liu et al. (2013) found that soil moisture was superior to precipitation in capturing the largest variations in spring grassland growth in Inner Mongolia. Additionally, a recent field experiment conducted in Inner Mongolia found that soil moisture was primary factor regulating spring grassland growth (Liu et al., 2022). We argue that soil moisture plays a prominent role in regulating grassland growth in recent years, which should receive considerably more attentions in the future.

Despite growing evidence of global greening since the early 1980s (Zhu et al., 2016), several studies have revealed that vegetation greening trend during the 1980s and the 1990s may have stalled or even reversed during the 2010s (Park and Sohn, 2010; Piao et al., 2011). Zhang et al. (2021) found that trend shift in vegetation growth in Inner Mongolia since 1999 was characterized by an interruption in the greening process followed by a continuous recovery process. These findings sparked a new research question, for instance, has the dominant factor causing vegetation greenness trend changed over the recent decade? To address this question, we separated the study period into two sub-periods: 1982–1996 and 2002–2016. Comparison between the two sub-periods showed that precipitation and short-term drought were the main factors determining the changes in grassland $NDVI_{GS}$ in most of Inner Mongolia prior to the mid-1990s, consistent with previous studies (Bao et al., 2014; Miao et al., 2020). However, during the second 15-a interval (2002–2016), the influence of precipitation and short-term drought was significantly reduced and even replaced by soil moisture. Studies suggest that precipitation and potential evapotranspiration are the two main factors influencing soil moisture regime in the Mongolian plateau over the recent decades (Meng et al., 2022). Therefore, an explanation for this shift could be that enhanced evapotranspiration resulting from climatic warming in Inner Mongolia offsets some of precipitation effect (Du et al., 2017). We do not reject the idea that there is no

contribution of precipitation to vegetation greening in Inner Mongolia, but we argue that precipitation acts as indirectly the source of soil moisture supplement (Salve et al., 2011; Schlesinger and Jasechko, 2014), and we emphasize the role of soil moisture in grassland growth, especially in recent decades.

4.3 Application of machine learning and statistical methods

Quantification and attribution of changes in vegetation greenness in arid and semi-arid areas using different linear models including residual analysis, correlation, and regression analysis mostly constrain climatic variables (Lü et al., 2015; Jiang et al., 2021). However, the response of arid grassland vegetation to climate change is often complex and non-linear (Peng et al., 2013; Piao et al., 2014). For instance, correlation among multiple factors cannot be explained well by conventional statistical methods due to their complex interactions. The collinearity among variables also makes it difficult to explain the response of vegetation change. Recently, machine learning (ML) approach has been utilized to overcome some of these statistical biases, as ML technique can resolve existing nonlinear problems and is less influenced by collinearity (Shi et al., 2020). Therefore, although LMG method can differentiate the contribution of correlated regression variables (Grömping, 2007), we found that BRT, a non-parametric machine learning method, was robust and complementary to LMG method. Despite having an ability to quantify, ML cannot fully clarify the mechanisms behind the relationship between vegetation growth and climate change. Further analysis and comparison of the results are required in conjunction with process-based models.

5 Conclusions

In this study, we observed an overall greening trend of Inner Mongolian grasslands in China from 1982 to 2016. Using the methods of MLR and BRT, we quantified relative contributions of temperature, precipitation, solar radiation, soil moisture, and SPEI-3 to changes in grassland $NDVI_{GS}$. We found that precipitation and soil moisture related to moisture regime were primary factors controlling changes in grassland $NDVI_{GS}$ from 1982 to 2016. This finding highlights the increased moisture deficits in vegetation greenness in Inner Mongolia, as soil moisture has replaced precipitation for grassland vegetation growth over recent decades. Increasing role of soil moisture in vegetation greenness in Inner Mongolia as revealed by a significant positive trend of grassland $NDVI_{GS}$ over recent period indicates complex relationship between grassland vegetation and climate change in the region. How the grasslands of Inner Mongolia respond to rapid climatic warming under increased water scarcity and the influence of soil moisture regime to vegetation growth are complex questions for scientific community as well as resource managers to address in the future.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization: MIAO Lijuan; Methodology: ZHANG Hui, MIAO Lijuan; Formal analysis: ZHANG Hui,

WANG Guojie, MIAO Lijuan; Writing - original draft preparation: ZHANG Hui, WANG Guojie, MIAO Lijuan; Writing - review and editing: Giri R KATTEL, CHUAI Xiaowei, ZHANG Yuyang; Supervision: MIAO Lijuan.

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